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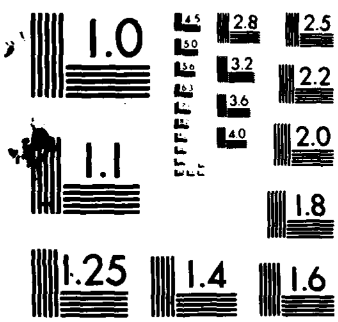

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In this grant research we have demonstrated efficient switching of high-power carbon dioxide laser radiation at picosecond speeds in the narrow-gap semiconductors indium antimonide, lead telluride, and mercury cadmium telluride. Excitation from a modelocked Nd: glass laser has been used to generate pulses of 10 micrometer radiation of approximately 2psec in duration by a dense transient electron-hole gas in these materials. This work takes advantage of the unique material properties of the narrow-gap semiconductors.

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20. Abstract cont'd

Our recently developed picosecond infrared techniques have been applied to the study, for the first time, the real time dynamics of dense, highly degenerate, transient electron-hole systems in PbTe, InSb, and Hg1-xCdxTe. In these experiments an intense ultrashort pulse generated a high density electron-hole gas (>1E19cm-3) through interband absorption. The optical properties of the excited system were then examined by picosecond infrared radiation at 10.6 and 5.3 micron wavelengths corresponding to probing of intraband and near band edge interband transitions, respectively. From time resolved decay measurements we have determined concentration dependent recombination rates, dominated most likely by rapid Auger processes. For example, a characteristic decay time of 40 psec was measured in PbTe at room temperature at an excess density of 1E10cm-3. Measurements for InSb and Hg1-xCdxTe have also yielded data for picosecond relaxation rates at the high excess densities and at varying temperatures. In interpreting the results, initial attempts have been made to include in the dielectric modeling the contribution by many-body effects, which appear to be quite significant in our experimental conditions. In this we have been aided by experimental measurements of the "dynamic" plasma edge ($\omega = \omega_p(t)$) and time varying interband transition rates (absorption and gain) at the probe beam frequencies.

The picosecond, high-intensity infrared pulses have also been used for a time-resolved investigation of nonlinear transmission in indium antimonide Self-induced shutoff of transmission was observed at 20 K and is attributed to avalanche generation and subsequent strong absorption by intervalence-band transitions. At higher temperatures, generation by two-photon absorption strengthens the effect. The apparent avalanche contribution is not accompanied by laser-induced damage such as occurs in larger-band-gap materials. The change from the transmissive to an opaque state occurs on a picosecond time scale.

Elsewhere we have theoretically examined the guiding of millimeter waves as interface electromagnetic waves (surface plasmons) in moderately doped semiconductors of high material quality. Specifically, we have calculated the propagation characteristics and modulation of surface plasmons in n-GaAs. Our results suggest that useful guiding and control of millimeter wave signals by these excitations may be possible.

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Contents

1. Research Objectives and Summary

The objective of the research under AFOSR Grant #77-3199 (1/1/77-12/31/81) was aimed at advancing the understanding and utilization of selected infrared material properties of narrow-gap semiconductors (primarily the HgCdTe and PbSnTe alloys). In particular, emphasis was placed on the interaction of such materials with high intensity ultrashort (picosecond) laser pulses and potential device applications of these semiconductors in high-speed infrared optical switching. In this, the grant work has been quite successful, as detailed below. Among the highlights of research achievements is the generation of picosecond high intensity CO_2 laser radiation at 10 μm wavelength region by ultrafast optical switching in HgCdTe and InSb. This accomplishment has been very much the first of its kind and represents a significant advance in the technology of ultrahigh speed infrared optics. In addition, the short pulses of infrared radiation have been applied for fundamental studies of highly excited electronic states in the narrow-gap semiconductors. A primary objective was the characterization and measurement of relaxation rates of a high-density degenerate electron-hole plasma in these materials. In this regard also, the research has yielded substantial novel results heretoforth only subject of broad theoretical guesswork.

The research results derived from this AFOSR sponsored grant have formed the basis of a number of scientific publications, as enumerated below. In addition to regular scientific meetings, the principal investigator has been invited to present the research results in several internationally recognized forums.

2. Research Accomplishments and Results.

(a) Development of Picosecond Infrared Switching in Narrow-Gap Semiconductors.

In this section we summarize the research which has led to generation of high power picosecond infrared radiation through the use of the readily available picosecond laser sources at shorter wavelengths in conjunction with a suitable optical switch for ultrafast modulation of an infrared beam of interest. Several physical mechanisms for such switching have been considered in the past including two-photon absorption and other third-order optical nonlinearities. We focussed our attention to simple mechanism, namely the modulation of infrared radiation by a high density optically injected excess electron-hole gas in a suitable semiconductor.

Classically, the contribution to the dielectric constant by a density of N electron-hole pairs can be written in a familiar way for photon energies below the energy gap:

$$\varepsilon(\omega) = \varepsilon_o - \frac{4\pi Ne^2/\bar{m}^*}{\omega(\omega+i/\tau)} + i\gamma N \qquad (1)$$

Here $\bar{m}^*$ is a suitably averaged reduced pair mass inclusive of band-structure effects, τ denotes intraband scattering time for the carriers (free electron and hole absorption) and γ is a cross section for additional damping processes such as intervalence band transitions (weakly dispersive) in semiconductors of zincblende symmetry. This simple description shows how a sufficiently dense free carrier gas (assumed thermalized) can subtract from the bound electron contribution ε_o and lead to a high reflectivity. The abruptness at which the transition to the highly

reflecting regime occurs depends to a significant degree on the damping coefficients γ and τ. These also contribute to loss of transparency through absorption. The enhancement of the effect through small effective masses suggests the use of narrow-gap semiconductors as a material for switching with economy of excitation although quite adequate results have been obtained by us earlier using high resistivity germanium.

A typical experimental arrangement developed by us recently to generate picosecond pulses in the 10 μm wavelength region is shown in Figure 1. Radiation from a TEA CO_2 laser is directed at a thin platelet or epitaxial film semiconductor switch, indicated schematically as two separate components in the encircled region of the figure. Near Brewster's angle of incidence ensures a very low initial reflectivity (and transmission through the complete switch). Alternatively, high quality antireflection

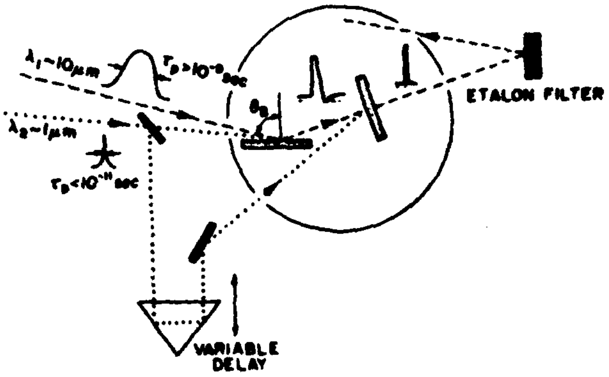

Figure 1: Schematic of experimental arrangement. The circle encloses both stages of the semiconductor switch, shown separately for clarity. The development of the 10 μm pulse envelope through the device is sketched qualitatively.

coated components may be used. Injection of a picosecond pulse from a short wavelength source (a modelocked Nd: glass laser at the first platelet will generate an abrupt increase in the reflectivity for the

10 μm radiation (in this case λ_2 = 1.06 μm although any wavelength shorter than the fundamental absorption edge of the semiconductor in question can be employed). Calculations show that for the narrow gap semiconductors presently employed by us (InSb, PbTe and $Hg_{1-x}Cd_xTe$) an approximate electron-hole density of $\gtrsim 10^{19}$ cm^{-3} is required for $R > .8$. This transient enhancement of reflectivity disappears as the electron-hole pairs recombine or diffuse toward the bulk of the semiconductor. Unlike for germanium where such recovery is typically longer than 100 psec, separate experiments by us have shown that e.g. for InSb the characteristic decay time is less than 40 psec dominated by a strong Auger recombination. The action of the ultrafast switch is completed at the second platelet where high reflectivity and opacity are now generated by a time delayed replica of the switching picosecond pulse. The abrupt termination of transmission thus leads to a switched out 10 μm pulse with a nearly constant amplitude and a duration which is variable over a sizable range through the action of a single translation stage.

For practical applications an important figure of merit is the ratio of the switched out infrared intensity to the unswitched background ("leakage"). In our arrangement a Fabry-Perot etalon filter is added for maximum transmission of the relatively monochromatic background. In contrast, the picosecond pulse is significantly spectrally broadened and thus reflected with high efficiency as an output from the device. In practise we have achieved peak-to-background intensity ratios for the picosecond pulses of better than 10^4: 1 with relative ease and without attempts to reach practicable limits.

Although nonlinear (second harmonic) optical correlation techniques

have been employed by us to measure the duration of the ultrashort 10 μm pulses, rather direct evidence can also be obtained by graphing the energy of the pulses against the "open time" of the switch (difference in arrival time of the two short wavelength picosecond pulses). Figure 2 shows such a measurement for a InSb switch. The linear region of the graph supports the assumption of a flat-topped pulse. For pulses of less than ∿ 4 psec in duration deviations occur due to the finite risetime and available peak power from our Nd: glass laser source. For even shorter time intervals the measured energy merges into the constant background (not particularly well filtered in this case). With our present apparata we estimate a lower limit to the duration of practically useful 10 *μm* pulses to be approximately 2 psec. Further reduction appears likely only with pulses of excitation which are correspondingly shorter (or possess a faster risetime).

At present, power densities at 10 μm of ∿ 1 MW/cm^2 from pulses TEA CO_2 lasers are routinely switched in our laboratory. Since the semiconductor materials in question can be prepared with relatively large areas (>1cm^2) the switching of rather large powers appears feasible. However, as has been shown by us in separate experiments, both electron heating and two photon absorption in intense infrared fields at 10 μm can lead to strong self-absorption for pulses of nanosecond duration for intensities only somewhat in excess of 1 MW/cm^2 e.g. for InSb [section c]. Such considerations place definite intensity limits for high power operation of picosecond switching in the narrow-gap materials. The situation is somewhat eased for a wider gap material such as germanium, but at the cost of increased excitation from the short wavelength source. For InSb we estimate that excitation density on the order of 1 $\mu J/cm^2$ should be sufficient to operate the switch with high

efficiency although maximal optimization has not been pursued by us so far.

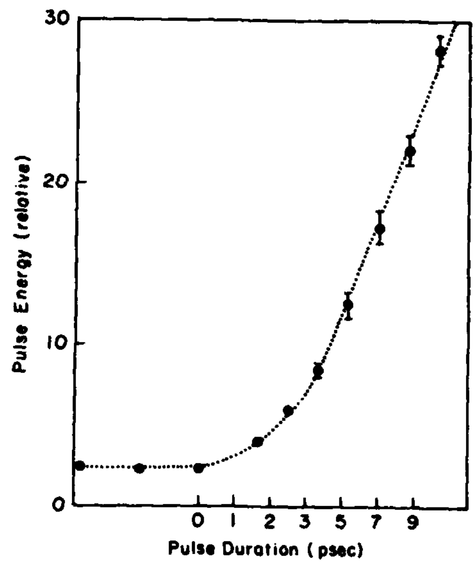

Figure 2: Transmitted infrared pulse energy vs. 'open time' of the switch (= pulse duration). Note that the horizontal scale factor is changed as deviation's from linearity begin to take place

In summary, we have reviewed results which show how optical switching of high power infrared radiation at picosecond speeds is a laboratory reality. Although work so far has centered around the 10 μm wavelength region the method is rather wavelength insensitive though longer wavelengths are favored in general. An additional technical requirement concerns the synchronization of the two laser sources, a problem of some technical challenge for lasers for which a relatively jitter free triggering is difficult. In the present instance the Nd: glass laser is synchronized to external events by a combination of intracavity Q-control and injection locking. An additional question of interest concerns the operation of the semiconductor switch at high repetition rates. In particular, we have estimated that operation in excess of 1 MHz is possible with a mode-locked cw source of excitation for a thin epitaxial film in direct contact with a good thermally conducting substrate.

(b) <u>Picosecond Spectroscopy of Highly Excited Electronic States in Narrow-Gap Semiconductors.</u>

The study of highly excited electronic states in narrow gap semiconductors suggests some interesting possibilities. For example, it may be possible to employ injection from a picosecond optical source to generate a dense electron-hole system for which such conventional parameters as quasi-Fermi and plasmon energies become comparable to or larger than the single particle energy gap. In particular, with development of picosecond optical sources near the 10 μm and 5 μm wavelength regions by us it was now feasible to examine the time-varying dielectric properties (intraband and interband) of a dense excess electron-hole gas. We performed the first experiments in InSb, $Hg_{1-x}Cd_xTe$, and PbTe to obtain information about the characteristic decay rates at densities typically about 10^{19} cm^{-3} and above. At the same time measurements of some interband transition rates suggested that electron-hole correlations may make significant contributions.

In our experimental arrangement a modelocked picosecond laser at 1.06 μm ($\hbar\omega \sim 1.17$eV) served as the primary source. By employing the short pulses to operate an ultrafast infrared switch, the output from a synchronously pulsed CO_2 laser at 10.6μm ($\hbar\omega \sim 117$meV) could be gated to generate high intensity radiation of variable duration on picosecond time scale [1].

Typically, for our purposes here, pulses of constant amplitude and 10-20 psec in duration were used and converted to 5.3 μm wavelength radiation through second harmonic generation in Te or $AgGaSe_2$ when needed. In an experiment, then, a sample of narrow-gap semiconductor was subjected to radiation from a $\sim$ 6 psec pulse of 1.17 eV photons thus leading to generation of a dense electron-hole gas near the surface. The time

varying optical constant of the system was then probed by recording the transmission and reflection of controllably time delayed 10.6 μm (or 5.3 μm) pulses. Figure 1 shows results for bulk InSb at room temperature (intrinsic material). The injection of the dense excess carrier gas causes an initially rapid change (limited by experimental resolution) in reflection and transmission. This is followed by a region of approximate constancy (whose duration increases with excitation) before the onset of a time resolved decay to equilibrium. The origin of time has been chosen to coincide with the approximate beginning of the decay. (Qualitatively similar data was obtained for $Hg_{1-x}Cd_xTe$ (x = .23, x = .30) and PbTe at room temperature. For comparable levels of excitation the decay was faster for $Hg_{1-x}Cd_xTe$ and slower for PbTe. In each case the intraband components ($\hbar\omega < E_{gap}$) were expected to dominate the dielectric response.

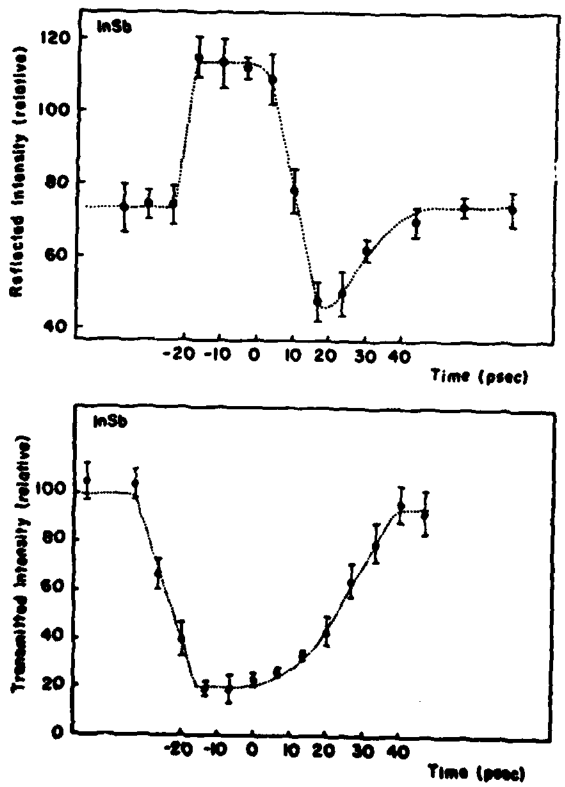

Figure 1. Time varying reflection and transmission at 10.6 μm in InSb at 300K as influenced by injection of a dense electron-hole gas

We have interpreted data such as in Figure 1 by employing a Drude-like model for a two component plasma with a k.p bandstructure in which known values for free carrier and intervalence band (not in PbTe) absorption have been extrapolated to our density regime as phenomenological damping parameters. It has been assumed that electrons and holes have thermalized with quasi-Fermi energies appropriate to lattice temperature. In the analysis we have not accounted for the influence of electron-hole scattering which may make a sizable contribution. It is noteworthy that the time resolved reflectivity shows the presence of the plasma 'dip' (not expected to be of significance in transmission due to absorption effects and the stratified nature of the medium). This permits the assignment of an approximate value for the instantaneous carrier concentration at that point. Thus for InSb we obtain an approximate decay constant of $\tau_D \approx 30$ psec for an 'initial' excess electron density of 8×10^{18} cm^{-3}. Similarly for PbTe $\tau_D \approx 50$ psec with an initial pair density $\Delta n = \Delta p \approx 1 \times 10^{19}$ cm^{-3} and $\tau_D < 15$ psec for $Hg_{.7}Cd_{.3}Te$ with $\Delta n = \Delta p = 1 \times 10^{19}$ cm^{-3}.

It is, of course, well known that for semiconductors such as InSb and $Hg_{1-x}Cd_xTe$ Auger recombination is a strong process, which can dominate recombination channels already at nondegenerate densities. In contrast very little experimental information is available in the highly degenerate regime [2]. Recently it has also been shown that for a multivalley "mirror band" semiconductor such as PbTe, scattering of carriers in different valleys of a band can enhance the otherwise weaker Auger rate [3]. Analysis of our data for PbTe at 300K shows that a rough agreement with a simple model can be made according to $dN/dt = WN^{-3}$, where W is an

Auger rate coefficient and equals approximately 1×10^{-28} cm^{+6} sec^{-1}. This value is consistent with earlier measurements in the nondegenerate regime, a rather surprising result considering the high degree of carrier degeneracy in our case. This is in strong contrast with our results for InSb and $Hg_{.70}Cd_{.30}Te$ which show very large deviations from extrapolations from the nondegenerate case. In a single valley model it has been pointed out by Haug [4] how degenerate statistics may significantly weaken the N^3 dependence aided further by effects of screening on the appropriate matrix elements. Further refinement of our present experimental techniques are still needed for a distinct determination of both the Auger cross-section and the concentration dependence.

An example of interband contributions is shown in Figure 2 where optical gain from a dense electron-hole gas is measured at 5.3 μm in PbTe at 20K. The temporal decay is comparable with the intraband data at room temperature.

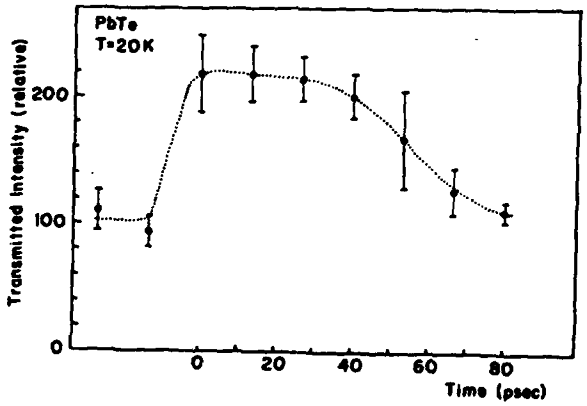

Figure 2: Time varying gain at 5.3 μm in PbTe at 20 K

On the other hand, direct calculations of maximum gain in a single particle Kane band model yield values significantly smaller than our observations. While estimates of the energy gap renormalization by exchange and correlation effects ($r_s \sim 0.1$) improve the agreement somewhat,

appreciable discrepancies remain. In this connection it may be useful to note recent calculations [5] which show how Coulomb interaction in the electron-hole (excitonic) continuum can lead to enhancement in inter-band transition rates as observed experimentally in GaAs [6]. Extrapolation to our case may be difficult, however, because of the significantly higher injection levels in our experiments and bandstructure effects in the narrow gap semiconductors.

1) S. A. Jamison and A. V. Nurmikko: Appl. Phys. Lett. 33, 598 (1978).

2) C. Benoit a la Guillaume and G. Fishman: Phys. Stat. Sol. 32, 269 (1969).

3) P. R. Emtage: J. Appl. Phys. 47, 2565 (1976).

4) A. Haug: Solid State Electr. 21, 1281 (1978).

5) R. Zimmerman: Phys. Stat. Sol. 86, K63 (1978).
K. Arya and W. Hanke: Solid State Comm. 33, 739 (1980).

6) D. von der Linde and R. Lambrich: Phys. Rev. Lett. 42, 1090 (1979).

(c) Nonlinear Transmission and Avalanche Breakdown in InSb, HgCdTe, and InAs in intense infrared fields.

The shaping of intense, infrared laser pulses in InSb was observed by Fossum et al. and later by Gibson et al. in their studies of two-photon absorption and plasma generation in this material and by Nee et al. in an investigation of the InSb spin-flip laser. The sources of radiation in these experiments were Q-switched and hybrid TEA CO_2 lasers having pulse durations of several hundred nanoseconds. Previous work in our laboratory centered on the investigation of the nonlinear transmission in several narrow-gap semiconductors with single nanosecond pulses from a mode-locked TEA laser. The use of shorter pulses eliminated the problems of sample heating and resulted in the first reported quantitative investigation of high-intensity transmission at 10.6 μm in InSb. The existence of an abrupt, high-intensity transmission limit caused by absorption from excess holes created by avalanche generation was noted. The transmission change occurred on a subnanosecond time scale. The results presented here are from a continuation of the study using pulses of still much shorter duration of 5-60 psec. We have again observed the self-induced shutoff of transmission of 10.6 μm radiation, but in the present instance the effect occurs at considerably higher intensities and on a picosecond time scale.

Our experimental arrangement is as shown in section (a) Pulses of 5-60 psec duration and of constant amplitude were switched out from the single-mode pulse (200-nsec) of a hybrid TEA laser. The 10.6 μm radiation was focused with a 50-mm focal-length ZnSe lens to a 500 μm-diameter spot size on the InSb sample, which was mounted on the cold finger of a liquid-helium-liquid-nitrogen Dewar. The InSb ($n = 5 \times 10^{13}$ cm^{-3} at 77 K) was carefully prepared by mechanical and chemomechanical polishing and had a thickness of 350 μm.

Typical experimental results are shown in Fig. 1 for 20,88,and 295K. For pulses shorter than 12 psec and up to 30 MW/cm^2 in intensity, no nonlinear transmission was observed at the two lower temperatures. Nonlinearity in the form of reduced transmission was noted for pulses of longer duration at the same intensity, with the effect being stronger at 88 K. At 295 K, nonlinear transmission occurred for pulses longer than 5 psec at 20 MW/cm^2. The results clearly show that the nonlinear effect occurs at lower intensities for pulses of longer duration and in samples at a higher temperature. This is consistent with the observations of Nee et al., who reported nonlinearity at $\sim$4 K for pulses above 2 MW/cm^2 at 40 nsec and of Fossum et al., who saw the onset of nonlinearity at

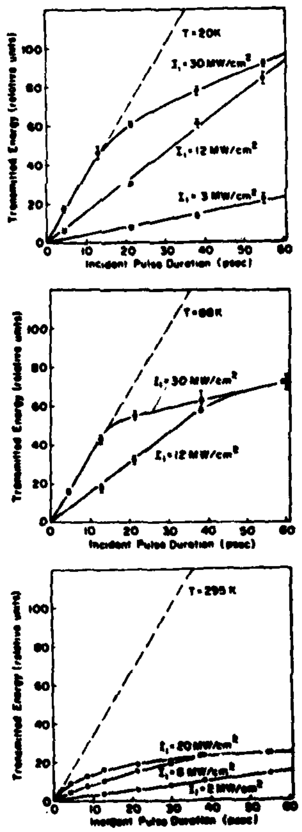

Fig. 1. High-intensity 10.6 μm transmission limit in InSb for ultrashort pulses at different temperatures. The lines are drawn to aid the eye. The dashed lines depict transmission of 30-MW/cm^2 pulses in the absence of nonlinearities.

77 K at around 1 MW/cm^2 for 100-1 nsec (FWHM) pulses. Gibson et al.[2] witnessed nonlinearity at 300 K below 1 MW/cm^2 at 50 nsec. For the single nanosecond pulses, an abrupt threshold occurred at 2 MW/cm^2 at 20 K, whereas at 77 K the onset of the nonlinear effect was more gradual and at a lower intensity.[4]

The derivative of the energy versus the pulse duration is the intensity versus the pulse duration. It is easy to see that at 88 K and 30 MW/cm^2, the transmitted pulse intensity is constant up to 12 psec, at which level it becomes greatly reduced in about 10 psec and remains constant at the lower value for the remainder of the pulse (at least up to 60 psec). It appears that for a pulse of 12-MW/cm^2 intensity, the change from high to low transmission occurs over a longer time.

A noticeable feature at 88 K and especially at 20 K is that the transmitted energy continues to increase after the change from high transmission to low transmission. This indicates that some radiation is getting through the sample after the transition to the opaque state. We believe that the radiation intensity in some portions of the beam is too low to cause nonlinear transmission. As this radiation travels through the sample without the additional attenuation experienced by the more intense portions of the beam, it continues to add to the transmitted pulse energy as the pulse duration is increased. When the weakest portions of the beam are intense enough to cause nonlinear transmission, the transmitted energy no longer increases for greater pulse durations. This is seen in the results for 295 K.

Previous work[1,2] was concerned with two-photon absorption in InSb and the subsequent strong absorption of 10.6 μm radiation by intervalence-band

transitions of the excess holes thus generated. With the band gap of InSb expanding from 180 meV at 300 K to 235.5 meV at 0 K, it was assumed that two-photon absorption and nonlinear transmission could not occur at very low temperatures when $2\hbar\omega < E_g$, an assumption that was supported by experiment.

In Ref. 4, a simple model was developed to estimate the excess electron-hole generation rate by hot conduction electrons that are excited by multiple absorption of infrared quanta. This was done by calculating the hot-electron energy distribution for different laser intensities and the matrix element for pair-production probability. An approximate time constant was derived for the buildup of excess carriers at the onset of the avalanche process. The calculation of the incident intensity at which the transmitted 10.6 μm radiation would be appreciably attenuated, (1/e) in 1 nsec, was in good agreement with the experimental result.

This simple model does not appear to extend readily to the picosecond time domain considered here. Most likely, the steady-state approximations that were acceptable for nanosecond pulses are not valid for picosecond pulses whose duration approaches the energy-loss time of hot electrons by optical phonon emission. Problems with the assumed parabolic energy bands are also more likely to occur for the higher-intensity picosecond pulses, which excite electrons farther above the conduction-band minimum. Nevertheless, the increase in radiation intensity required for observation of nonlinear transmission for ultrashort 10.6 μm pulses is consistent with the model.

In conclusion, our time-resolved experiments using ultrashort, high-intensity 10.6 μm pulses to study nonlinear transmission in InSb at low

temperature show that the self-induced shutoff of transmission by avalanche generation and the subsequent intervalence-band transition occur on a picosecond time scale. At higher temperatures, additional generation by two-photon absorption strengthens the nonlinear effect. The avalanche process does not result in laser-induced damage such as occurs with larger band-gap materials. The observed higher radiation intensities that are required to initiate avalanche with ultrashort pulses are only qualitatively consistent with previous theory.

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5. S. A. Jamison and A. V. Nurmikko, Appl. Phys. Lett. 33, 598-600 (1978).

(d) Work on Far-Infrared and Millimeter Wave Devices

We have also made progress in two additional areas which are connected with newly initiated research efforts to study nonlinear optical effects involving polaritons (plasmon-phonon) at mid-and far infrared wavelengths. The summaries of each are given below.

(a) We considered the guiding of millimeter waves as interface electromagnetic waves in moderately doped semiconductors of high material quality. Specifically, we examined the propagation characteristics and modulation of surface plasmons in n-GaAs. Our results suggested that useful guiding and control of millimeter wave signals by these excitations may be possible.

(b) We have investigated the generation of high power, subnanosecond near-mm wave pulses, obtained by synchronous pumping with a modelocked TEA CO_2 laser of CH_3F (496 μm, 193 μm) and D_2O (385 μm, 66 μm) and NH_3 (151 μm). The dependence of pulse duration on pressure and cavity detuning have been studied, together with the dynamic evolution of the pump and FIR pulses.

3. Scientific Publications and Presentations Resulting From Grant Research

The following publications have resulted directly from AFOSR grant support and have been so acknowledged:

1). "High Intensity Infrared Transmission Limit in $Hg_{1-x}Cd_xTe$", with S. A. Jamison, Appl. Phys. Lett. 33, 182 (1978).

2). "Generation of Picosecond Pulses of Variable Duration at 10.6 m", with S. A. Jamison, Appl. Phys. Lett. 33, 598 (1978).

3). "Ultrafast Optically Activated Switching in Semiconducting Materials", with S. A. Jamison, in Physics of Fiber Optics, Plenum Press (1979), p. 431.

4). "High Intensity Infrared Transmission Limit in Narrow-Gap Semiconducting Materials", Proc. Int. Conf. of Physics of Semiconductors, Edinburgh (1979), p. 315.

5). "Avalanche Formation and High Intensity Infrared Transmission Limit in InAs, InSb and $Hg_{1-x}Cd_xTe$", with S. A. Jamison, Phys. Rev. B19, 5185 (1979).

6). "Generation of Ultrashort Pulses in Synchronous Pumping of Near-Millimeter Wave Lasers", with W. Lemley, J. Infrared and MM-waves 1, 85 (1980).

7). "Guiding and Control of Millimeter Waves by Surface Plasmon Phenomena in Semiconductors", A. V. Nurmikko, D. M. Bolle and S. Talisa, J. Infrared and MM-waves 1, 3 (1980).

8). "Nonlinear Transmission of Picosecond 10.6 m pulses in InSb", B. D. Schwartz and A. V. Nurmikko, Optics Letters 5, 371 (1980).

9). "Picosecond Infrared Spectroscopy in Narrow-Gap Semiconductors", B. D. Schwartz and A. V. Nurmikko, in Picosecond Phenomena II, Springer-Verlag Series in Chemical Physics vol. 14 (1980), p. 303.

10). "Picosecond Spectroscopy of Highly Excited Electronic States in Narrow-Gap Semiconductors", A. V. Nurmikko and B. D. Schwartz, Proc. 15th Int. Conf. Phys. Semic., J. Phys. Soc. Japan 49, 511 (1980).

11). "Generation of High Power Picosecond Infrared Radiation by Ultrafast Optical Switching", A. V. Nurmikko and B. D. Schwartz, Proc. Int. Conf. Lasers. '80, Soc. Quant. Electr., p. 190 (1981).

12). "Optical Studies of a High Density Electron-Hole Plasma in PbTe", B. D. Schwartz, C. A. Huber, and A. V. Nurmikko, in Proc. Int. Conf. Narrow-Gap Semiconductors, Linz, Springer-Verlag (1982).

13). "Some Properties of a High Density Electron-Hole Plasma in HgCdTe", A. V. Nurmikko and B. D. Schwartz, J. Vac. Soc. (in print)

The following conference appearances (invited and contributed) have also been made to describe the AFOSR supported work:

Invited Lectures (1978)

Yale, Solid State Physics Seminar, May 1978

Papers Presented (1978)

International Quantum Electronics Conference
Atlanta, Ga., May 1978

International Conference on Picosecond Phenomena,
Hilton Head, S. C., June 1978

Conference on Physics of Fiber Optics,
Kingston, R. I., June 1978

International Conference on Physics of Semiconductors,
Edinburgh, Sept. 1978

Papers Presented in 1979

International Conference on Infrared and Millimeter Waves,
Miami, Fla, December, 1979 (two papers)

Invited Lectures and Papers (1980)

- Workshop on High Speed Optoelectronic Devices, Lexington, MA, April 1980.
- M.I.T., Quantum Electronic Seminar, Sept. 1980.
- Honeywell (Minneapolis) Corporate Research Laboratories, October 1980.
- International Conference on Lasers '80, New Orleans, December 1980.

Papers Read (1980)

- American Physical Society, March Meeting, New York two papers.
- XI International Conference on Quantum Electronics, Boston, June 1980
- Conference on Picosecond Phenomena, Cape Cod, June 1980.
- International Conference on Physics of Semiconductors, September, Kyoto Japan.

Invited Lectures and Papers (1981)

- International Conference on Excited States and Multiresonant Optical Processes in Solids, Aussois, France, April 1981
- University of Toronto, Physics Department Colloquium, Toronto, March 1981
- Conference on the Physics and Chemistry of HgCdTe, Minneapolis, October 1981

Papers Read (1981)

- International Conference on the Physics of Narrow-Gap Semiconductors, Linz, Austria, Sept 1981

4. Personnel

The following have had direct support from this AFOSR Grant:

Prof. A. V. Nurmikko, Principal Investigator

Dr. S. Jamison (1978-1980); now at Honeywell Corporate Materials Sciences Center, Bloomington, Minnesota

B. D. Schwartz, Graduate student getting his Ph.D. 3/32

C. A. Huber, Graduate student, will obtain Ph.D. approximately 1/83

5. Patents

NO patents have been filed in connection with this AFOSR sponsored research

6. Remaining Funds (see also final fiscal report)

No funds have remained from the last grant period, expired 12/31/81.